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LCA METHODOLOGY

Application of life cycle assessment in the mining industry

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Abstract
Background, aim, and scope In spite of the increasing application of life cycle assessment (LCA) for engineering evaluation of systems and products, the application of LCA in the mining industry is limited. For example, a search in the Engineering Compendex database using the keywords "life cycle assessment" results in 2,257 results, but only 19 are related to the mining industry. Also, mining companies are increasingly adopting ISO 14001 certified environmental management systems (EMSs). A key requirement of ISO certified EMSs is continual improvement, which can be better managed with life cycle thinking. This paper presents a review of the current application of LCA in the mining industry. It discusses the current application, the issues, and challenges and makes relevant recommendations for new research to improve the current situation.
Main features The paper reviews the major published articles in the literature pertaining to LCA methodology as applied in the mining industry. The challenges associated with LCA applications in mining are discussed next. Finally, the authors present recommended research areas to increase the application of LCA in the mining industry.
Results The literature review shows a limited number of published mining LCA studies. The paper also shows the variation in functional unit definition for mining LCA studies. The challenges and research needed to address the problems are highlighted in the discussions.
Discussion The limited number of mining LCAs may be due to the lack of life cycle thinking in the industry. The paper, however, highlights the major contributions in the literature to LCA practice in the mining industry. This paper discusses the lack of LCA awareness and tools for mining LCAs, issues relating to functional unit and scoping of mining product systems, defining adequate and appropriate impact categories, and challenges with uncertainty and sensitivity analysis. The authors recommend that future research focus on the development of a mining-specific LCA framework, data uncertainty characterization, and software development to increase the application of LCA in mining.
Conclusions LCA presents beneficial insights to the mining industry as it seeks to develop world-class EMSs and environmentally sustainable projects. However, to take full advantage of this technique, further research is necessary to improve the level of LCA application in mining. Major challenges have been identified, and recommended research areas have been proposed to improve the situation. The paper outlines the benefits of increased application of LCA in the mining industry to LCA databases and all practitioners.
Recommendations and perspectives It is recommended that additional research be undertaken through industry–academia partnerships to develop a more rigorous mining-specific LCA framework. Such a framework should allow for sensitivity and uncertainty analysis while allowing for suitable data collection that still covers the temporal and spatial dimensions of mining. Research should also be carried out to develop objective ways of characterizing the uncertainty introduced in a LCA study due to the use of secondary data (emissions

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factors) from prior studies. Finally, new software or GUIs that address the peculiarities of mining should be developed to help mining professionals with basic LCA knowledge to undertake LCA studies of their systems and mines.

Keywords LCA methodology · Life cycle assessment · Mining · Sensitivity analysis · Uncertainty analysis

1 Introduction

Since the formalization of environmental life cycle assessment (LCA) by the Society of Environmental Toxicology and Chemistry (SETAC) in the early 1990s, the approach has been widely used in assessing the environmental impacts of various products and systems (Basset-Mens et al. 2007; Battisti and Corrado 2005; Chaya and Gheewala 2007; Socolof et al. 2005). LCA proposes a cradle-to-grave approach to evaluating the environmental impacts of a product or system. This approach provides a comprehensive way to evaluate benefits to society of particular policy choices, product preferences, and system improvements. In this cradle-to-grave approach, every unit process is tracked back to the raw materials and energy inputs and forward to the disposal impacts. Most industrial processes have mined products as raw materials or coal-generated or nuclear electric power as inputs. Yet, there is limited mining application of LCA found in the literature. For instance, a search in EI Compendex with the keywords "life cycle assessment" yields 2,257 results, whereas the same search yields 19 results (80 total results but only 19 significantly address the processes that occur in the mining lease area, e.g., Amatayakul and Ramnas (2001) has nothing on mining processes but shows up in the 80 results when combined with the keyword "mining." The limited number of mining LCAs undermines the many life cycle inventories that have been developed, since every product system consumes the products of mining directly or indirectly (e.g., by utilizing electricity produced by coal-fired power plants). Additionally, most mining operations are adopting ISO 14001 certification of their environmental management systems (EMSs). A key requirement of an ISO-certified EMS is continual improvement of the process or upstream processes. The lack of mining LCAs limits the ability of management to require improvements of the most significant supplier or make changes to the most important process. Finally, comprehensive LCA studies will provide additional insights into technology choices in mining, as well as the environmental impacts and benefits of mining permit conditions.[1] For instance, what are the life cycle environmental impacts of backfilling a surface mine after mining as compared to reclaiming both the pit and waste pile separately for post-mining land uses?

This paper reviews the current state of LCA in relation to the mining industry and the challenges and issues to be addressed in order to increase the application of life cycle methods in the industry. This is done by reviewing the existing literature to establish the current level of LCA application in the mining industry, identifying the major issues and challenges affecting the application of LCA in mining, and recommending steps to assist in increasing the use of LCA thinking in the mining industry. The paper assesses the specific needs of the mining industry vis-à-vis LCA and thus contributes to work that improves the chances of applying LCA techniques in engineering evaluation and government policy (both in terms of new regulation and general attitudes toward mining). The next section presents a review of the existing literature on mining applications of LCA. Section 3 presents the discussion on the challenges and issues that hamper the use of LCA techniques in the mining industry. Section 4 presents some of the research needs necessary to overcome the challenges and improve the use of LCA in the mining industry, and Section 5 is the concluding section.

2 Current LCA applications in mining

Mining provides most of the raw materials for industrial processes and products. Coal mining provides about half (48.5% in 2008) of the net electricity generated in the USA (US Energy Information Administration 2008). In LCA studies, the mining system is often represented as a black box, not lending itself to the interpretation of the different processes used in coal and minerals production. The generic data used are often inadequate for a mining LCA and cannot be used as an accurate account of the spatial and temporal mining environmental burdens that contribute to more complex systems "down-stream," such as metals, building, chemical, or food industries (Durucan et al. 2006). Consequently, the lack of mining LCAs in the literature is worrisome.

In spite of the low application of life cycle thinking to decision making in the mining industry, some examples of mining LCA studies can be found in the literature (Awuah-Offei et al. 2008a, b; Bovea et al. 2007; Durucan et al. 2006; Mangena and Brent 2006; Spitzley and Tolle 2004; Suppen et al. 2006). The goals of these LCAs vary and include estimating land-use equivalency factors (Spitzley and Tolle 2004), identifying high impact processes during mining, treating and marketing of red clay (Bovea et al. 2007), evaluating the life cycle environmental impacts of different grades of coal mined with different mining methods (Mangena and Brent 2006), and life cycle environmental impact assessment of mine haulage options in surface mines

[0] These are conditions imposed on the mining operation by the government agency that issues the mining permit.

(Awuah-Offei et al. 2008a). The diversity of the motivation behind these studies shows the versatility of the LCA methodology and its potential in the mining industry. LCA can provide unique insights in the analysis, and evaluation, of a host of issues and options in the mining industry. The boundaries of the product systems used in these studies also vary. Suppen et al. (2006) recognize the temporal nature of mining activities from exploration to decommissioning as proposed by van Zyl (2005). On the contrary, others ignore the temporal aspects, often providing little or no justification (Bovea et al. 2007; Durucan et al. 2006; Mangena and Brent 2006). It should be recognized that, depending on the mine life, the onetime processes of exploration and mine closure and decommissioning will contribute very little to the inputs and outputs per functional unit. Of the reviewed mining LCA studies, Awuah-Offei et al. (2008a) is the only one that used a quantitative scoping method.

Like all other life cycle inventories (LCIs), the mining LCIs draw their data from varied sources including company websites and publicly available data (Spitzley and Tolle 2004), detailed surveys and data collection at mine sites (Durucan et al. 2006), and industry-wide statistics and government reports (Mangena and Brent 2006; Suppen et al. 2006). Based on their developed framework for mining LCA and the corresponding product system (Fig. 1), Durucan et al. (2006) developed an extensive LCI based on mine equipment inventories, productivities, and energy consumptions. Given the differences in mining methods and systems and the limited number of studies with mining unit processes (e.g., drilling, blasting, excavation, hauling, crushing, and screening), building mining LCI has to be based on detailed data collection at the mine. This is not always

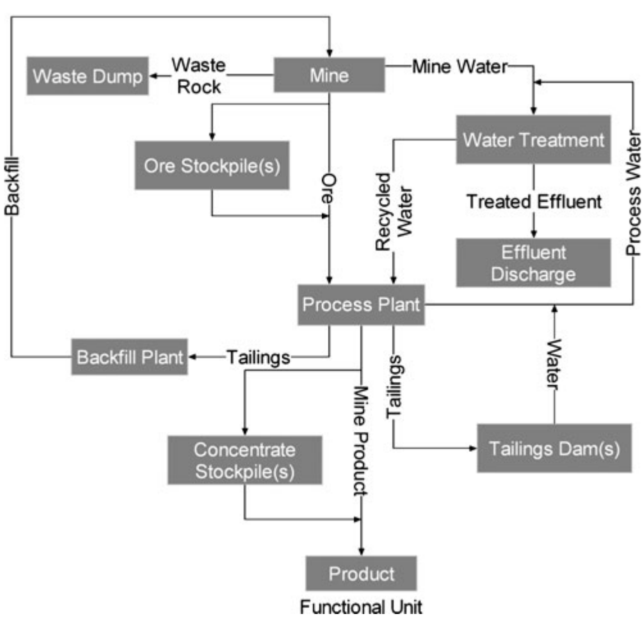

Fig. 1 Mining product system (after Durucan et al. (2006))

possible or easy for researchers to do due to how sensitive mining companies are of divulging environmental and reserve information.

Mining LCA studies have adopted some of the same impact categories as all other studies. However, various authors have recognized the fact that the standard impact categories (global warming, ozone depletion, human toxicity, fresh water aquatic ecotoxicity, acidification, and eutrophication potential impacts) are not enough to describe the environmental impacts of mining. Land-, water-, and energy-use impacts and resource depletion are some of the impacts that have been suggested as equally important in mining LCA (Durucan et al. 2006; Mangena and Brent 2006; Spitzley and Tolle 2004). Spitzley and Tolle (2004) dealt with the issue of land-use impacts in LCA methodology and proposed average lifetime disturbed area per unit of ore production as a measure of land use potential impacts. The limitations of this measure include the following: (1) it is difficult to compare systems with different annual disturbed land area (e.g., underground versus surface mining methods), (2) it could potentially under-estimate the effect of land quality, (3) annual disturbed land area tends to vary significantly from year to year, and (4) it does not provide any information on the long-term effects of the land use on the ecosystem. However, lifetime disturbed area per unit of production (acre-year per ton) provides a quantitative assessment of the surface area occupation aspect of land-use impacts and facilitates easy comparison between alternate land uses. Land-use impacts may not be a priority in the UNEP/SETAC Life Cycle Initiative, as noted by Udo de Haes (2005), but are very relevant to mining communities, professionals, and companies. Given the relevance of these stakeholders in any LCA of mining activities, land-use impacts should be considered a relevant impact category if the goal and scope of the LCA permits. Benetto et al. (2006) proposed a fuzzy logic-based method of assessing the life cycle impacts of noise using both an open cast and an underground mine to validate their model. The work does not adequately account for mobile equipment and the temporal and spatial dimensions of the noise impacts of mining. However, the introduction of the life cycle impacts of noise is unique, and their work illustrates the challenges of incorporating some of the impacts local communities care about the most into the LCA framework.

Uncertainty and sensitivity analysis in the mining LCA studies reviewed is limited, much like life cycle studies in general (Ross et al. 2002). For example, the mining life cycle program developed by Durucan et al. (2006) does not allow for uncertainty and sensitivity analysis and, thus, limits its application in decision-making (US EPA 1995, 2003, 2006). Awuah-Offei et al. (2008a), on the other hand, uses Monte Carlo simulation and multi-variable regression for uncertainty and sensitivity analysis, respectively. Bovea

et al. (2007) incorporated some uncertainty analysis by using three different methods for impact assessment (Eco-Indicator 1995 (Goedkoop 1995), Eco-Indicator 1999 (Goedkoop and Spriensma 2000), and EPS 2000 (Steen 1999a, b)). Evidently, the examples of LCA studies that focus on the mining phase of products have made contributions in the attempt to adopt LCA methodology to the mining product system.

3 Challenges to LCA applications in mining

3.1 LCA awareness and tools

Engineering evaluation using LCA presents encouraging opportunities and insights to the mining industry. These include quantitative ways of improving EMSs, providing information for stakeholders, and helping meet sustainable development goals. Increasing numbers of mining companies are developing sustainable development goals, which will need LCA insight to better assess the impacts of mining activities (BHP Billiton 2006; Rio Tinto 2006). Yet, there is only a limited amount of life cycle thinking among mining professionals which can be attributed to the limited amount of mining-related life cycle research and data. Consequently, most LCA examples, data, and software tools do not address the peculiarities of the mining industry. In fact, LCA emission factors for specific mining unit processes are not publicly available at the moment. The publicly available sustainability reports provide, at best, data for a whole mine but often data for an entire company since they are corporate reports (BHP Billiton 2006; Rio Tinto 2006). This makes it difficult for LCA methods to be applied by mining professionals in their everyday work and decision making.

3.2 Functional unit and scoping

Most LCA studies differ fundamentally in the functional unit and the product system. The functional unit will typically be stated in terms of a unit of production. However, a functional unit in terms of the rate of production (e.g., tons per hour) may be better suited for comparative studies in mining since the scale of the project and, consequently, the emissions profile depend on the productivity of the mine. Different products may require the functional units to be stated in terms of refined product instead of quantity of ore production (e.g., pounds of copper instead of tons of copper ore). Even for the same product, whether the mine has an on-site processing plant[2] or not will necessitate different functional units. This could potentially result in varying functional units that make it difficult to generate emission factors from the studies. Mines with multiple products (e.g., copper mines with molybdenum) will not only present allocation problems but also problems with specifying the functional unit. For instance, Forbes et al. (2000), in conducting a LCA study of base metal refining, use a functional unit of 1 t of nickel despite the co-production of copper, cobalt, and ammonium sulfate and a host of precious metals. The authors recognize the resulting overestimation of the life cycle impacts of nickel and caution against using the impacts in their study without prior allocation. Table 1 illustrates the diversity of functional units used in mining LCAs. Spitzley and Tolle's (2004) work is a good example of how the functional units of mining products may affect comparative LCAs. In comparing the land-use impacts of copper, gold, and aluminum production, they used 1 t of refined metal as the functional unit in spite of the significantly different economic values per ton of the products.

Life cycle scoping should be quantitative if at all possible (ISO TC 207 2006). The relative mass energy economic (RMEE) value method of scoping method is a quantitative scoping method that can be applied to mining life cycle product systems (Raynolds et al. 2000). The RMEE method, however, is limited in cases where the functional unit is a high mass but low energy content material (e.g., metal ore). In such instances, the RMEE method can be modified to ignore the energy value and use different cut-off ratios for economic value and mass (Awuah-Offei et al. 2008a, b). Additionally, mining product systems should be constructed to take into account the temporal and spatial dimensions of mining. Mining projects change over time from mine development (shaft sinking, facilities construction, etc.) to mine closure and decommissioning. In the case of deposits with long mine lives, the overall contributions of the emissions from these processes to the impact per functional unit are minimal. However, this is not always the case, and quantitative approaches, such as the RMEE method, can be used to determine whether to include such processes in the product system or not.

3.3 Impact categories

The usual impact categories—global warming, ozone depletion, human toxicity, fresh water aquatic ecotoxicity, acidification, and eutrophication potential impacts—are suitable for mining LCA studies (CML 2001; ISO TC 207 2004). Additionally, land-, water-, and energy-use impacts are also suitable for mining LCA (Durucan et al. 2006; Mangena and Brent 2006; Spitzley and Tolle 2004). Durucan et al. (2006), while including abiotic resources depletion in their LCA study of mining, recognized that the current methods are inadequate for mineral extraction LCA. Energy resource depletion will be a much more useful

[0] Processing plant is used here to refer to a plant that processes the ore to a useful product ready for use or requiring only refining.

Table 1 Variation in mining functional units

Source	Functional unit	Mining product
Awuah-Offei et al. (2008a)	4,000 t/h of rock delivered to dump sites (waste dump and ROM Pad)	Gold
Bovea et al. (2007)	1 t of clay as produced and sold	Red clay
Durucan et al. (2006)	1,250 t/day of bauxite	Bauxite
Spitzley and Tolle (2004)	1 t of refined metal	Gold, aluminum, and copper
Suppen et al. (2006)	1 t of concentrated mineral	Base metals
Mangena and Brent (2006)	1 t of delivered coal product	Coal

impact category especially for those mining products that are for energy generation (coal, oil sands, and uranium). The energy generation mix of the area should then be used to account for the consumption of the product in its own production (e.g., consuming coal-fired electricity to produce coal). Land use is an appropriate impact category for mining because of the long periods of exclusive use. In some cases, land once used for mining forever precludes other uses. The case for including land use in life cycle impact assessment (LCIA) has been made by several authors and was the subject of the Taskforce on Resources and Land Use within the UNEP-SETAC Life Cycle Initiative Working Group on LCIA (Canals et al. 2007; Chapin et al. 2000; COM 2002; EEA-UNEP 2000; Müller-Wenk 1998; Pimentel et al. 1995; Sala et al. 2000). Appropriate measures of land surface area occupation should suffice for mining land-use impacts (Spitzley and Tolle 2004). An appropriate measure should capture the fluctuating amounts of disturbed lands during the life of a mine, land quality, and mine reclamation (preparing the land for the predetermined post-mining land use) in relation to established post-mining land use. For comparative mining LCA studies, the eight impacts (global warming potential, ozone depletion potential, human toxicity potential, fresh water aquatic ecotoxicity potential, acidification potential, eutrophication potential, land-use impacts, and energy-use impacts) and the relative significance of the impacts should be established to facilitate easy decision making. Alternatively, the relative impact indicator approach could be used to reduce the performance measures or the environmental performance relative impact indicator (EPRII) approach to aggregate all impacts into a single total EPRII for decision making (Mangena and Brent 2006).

3.4 Uncertainty and sensitivity analysis

The application of uncertainty and sensitivity analysis to quantify confidence in environmental model (including LCA models) results is important for the model to be appropriately used to inform decisions (ISO TC 207 2006; US EPA 1995, 2003). Yet, Ross et al. (2002) report that only 3% of LCA studies employ quantitative uncertainty analysis with another 7% employing qualitative uncertainty analysis. Of those that employ quantitative uncertainty analysis, the majority use stochastic modeling (particularly Monte Carlo simulation, e.g., Awuah-Offei et al. 2008a). However, most LCA studies are done with limited data, which limits the LCA practitioner's ability to do statistical goodness-of-fit tests, an important step for Monte Carlo simulation. This has led to an attempt to use other methods of uncertainty analysis such as interval calculations (Chevalier and Le Téno 1996), fuzzy data sets (Tan et al. 2002), uncertainty propagation (Aquilonius et al. 2001), and Bayesian statistics (Lo et al. 2005). However, these methods either introduce subjectivity or do not provide a full risk profile of the impacts. Bayesian statistics suffers from the same limitation as Monte Carlo (and Latin Hypercube) simulation in choosing a prior distribution. Therefore, Monte Carlo simulation remains the method of choice in LCA uncertainty analysis. Lloyd and Ries (2007) report that 67% of LCA studies that undertake quantitative uncertainty analysis use stochastic modeling (Monte Carlo and Latin Hypercube), 29% scenario probabilities, 17% fuzzy data sets, and 8% uncertainty propagation. The challenges associated with rigorous uncertainty analysis will have to be overcome if LCA is to become an important decision-making tool in the mining industry.

4 Recommended research areas

4.1 Mining specific LCA modeling framework

In order to develop mining-specific LCA software, a generic mining-LCA framework appropriate for numerical modeling and programming is necessary for software implementation. The generic product system in Fig. 1 developed by Durucan et al. (2006) can be a basis for such a framework. However, it is possible to develop the products and emissions of these unit processes without the level of detail they adopted and the attendant problems: (1) how to deal with the many concurrent sub-activities, (2) insufficient data for inputs and impacts for each sub-activity, and (3) difficulty calculating and assigning inputs

and impacts to each sub-activity. To avoid these problems, each unit process in Fig. 1 can be treated as a life cycle product system. Product systems for each of the unit processes can be developed to make it feasible to conduct a LCI for the resulting product system.

Figure 2, for example, shows the product system for the "Process Plant" unit process in Fig. 1. The advantages to this approach are as follows:

1. Ease of data collection due to compatibility of the unit processes with standard LCI databases;
2. The temporal and spatial dimensions of a mining system are honored without creating an unfriendly user interface. For instance, with this approach, a list of all equipment on the mine site need not be generated since each department head will account for his/her equipment in evaluating his/her sub-systems impacts;
3. This approach is more consistent with the way mines assess their environmental impacts and will make it easy to work with; and
4. Improvements will be easy to design since further investigation to understand high impact unit processes will be more meaningful.

4.2 Characterizing data uncertainty

There are three sources of uncertainty in LCA models: variations in collected (primary) data, uncertainty introduced by using secondary data from other LCAs, and uncertainty in equivalence factors based on impact assessment models. In the case of primary data uncertainty, the issues have been discussed above. More research is necessary to overcome the limitations of stochastic simulations and the other alternatives. With regards to secondary data, tools need to be developed to guide LCA practitioners to, more objectively, quantify the introduced uncertainty due to the differences between the systems analyzed with the data and the system under study. One such approach will be the application of fuzzy logic models to assign quality indices based on expert opinion. The advantage of fuzzy logic models in this application is that they are superior in converting linguistic terms into numerical or quantitative equivalents. Hence, a fuzzy logic model could be used to convert expert opinion of the data uncertainty (e.g., good, fair, or poor) into quantitative indices that describe the level of uncertainty. Such indices will then be correlated to the measure of uncertainty in the uncertainty characterization model (e.g., standard deviation in Monte Carlo simulation). This model should take into consideration geography, age of data, technology, transportation system, size of operation, energy sources, and allocation method. The Takagi–Sugeno–Kang (TSK) method of fuzzy inference will be a suitable system for such a model (Sugeno 1985). The TSK method has been shown to be superior with respect to computational time than the rival Mamdani method (Jassbi et al. 2006). It is also more robust and accurate in working with noisy data as compared to the Mamdani method (Jassbi et al. 2007).

Additionally, impact assessment models, which are used to derive the equivalence factors for different emissions, have inherent uncertainties. In the case of mining LCA, some data uncertainty is due to the selection of impact categories. The standard list of LCA impact categories is not very well suited for assessing the environmental impacts of mining (Durucan et al. 2006; Mangena and Brent 2006; Spitzley and Tolle 2004). This leads to a situation where uncertainty is introduced in the decision-making process due to the number and type of impact categories chosen. Further research is required to develop and/or refine proposed impact categories and factors that are better suited for assessing the environmental impacts of mining systems.

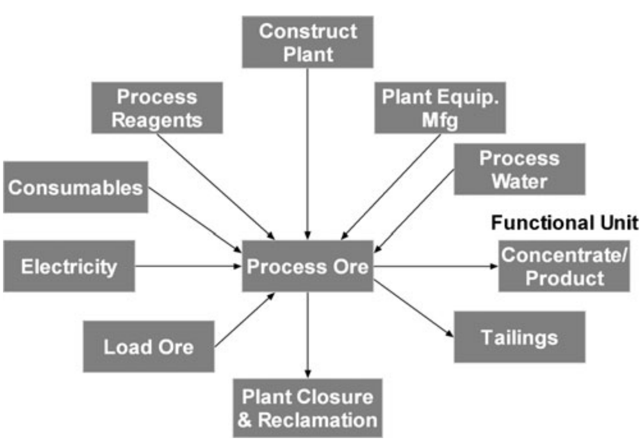

Fig. 2 Process plant product system

4.3 Mining LCA software development

More mining-specific LCA software like the LICYMIN developed by Durucan et al. (2006) need to be developed to facilitate LCA studies in the mining industry. Some of the problems with the framework of the LICYMIN have been discussed above in detail. These will require further research to overcome. However, any future software development should also allow the user to undertake uncertainty analysis, sensitivity analysis, and comparative studies of different mines or mining systems. Alternatively, forms and GUIs in current commercial LCA software can be developed (e.g., creating wizards in SimaPro 7.1 (PRé 2008)) to assist mining professionals with some level of LCA knowledge to easily and quickly undertake LCA studies of their systems or mines.

5 Conclusions

In spite of the extensive consumption of mining products in all industrial processes, there is no widespread application of LCA in evaluating mining systems and technology. The limited number of mining LCA studies, and resulting emissions factors, undermines the accuracy of other LCA data and emissions factors. Also, it provides no opportunity for engineering evaluation of mining systems using LCA methodology. As more mining companies develop sustainable development programs, the insight provided by LCA will be invaluable to management. As part of the push towards good global citizenship, mining companies have been adopting ISO 14001 certification of EMSs. Without LCA, the improvement of a mine's EMS is ad-hoc and suboptimal. This review paper presents the state of LCA vis-à-vis the mining industry through a critical review of the current literature. The lack of LCA awareness, the challenges of defining a functional unit and product systems scoping, defining appropriate impact categories, and issues surrounding uncertainty and sensitivity analysis are presented as possible reasons for the lack of widespread acceptance in the industry. It is recommended that future research concentrate on developing a rigorous mining-specific LCA framework. Other areas that need research attention include uncertainty characterization and software tools. These steps will help to bring LCA thinking to the mainstream of mining engineering.

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